Coupled Mesoscale Modeling of the Atmosphere and the Ocean

Richard M. Hodur, Julie Pullen[1], Xiaodong Hong, James A. Cummings[2], and James D. Doyle

Naval Research Laboratory
Monterey, CA 93943-5502

[1]Consortium for Oceanographic Research and Education (CORE) Postdoctoral Fellowship Program
Naval Research Laboratory
Monterey, CA 93943-5502

[2]Naval Research Laboratory
Stennis Space Center, MS 39529-5000

Abstract

The Naval Research Laboratory (NRL) has developed the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS™[1]). COAMPS is comprised of atmosphere and ocean data assimilation systems. The atmospheric portion of COAMPS has been running operationally at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) since 1998, and it has been found to be valuable for the prediction of mesoscale weather events in the coastal zone, and areas of significant topography. A multivariate optimum interpolation (MVOI) analysis is used to construct analyses of the atmosphere using observations from radiosondes, satellites, ships, buoys, aircraft, etc. The atmospheric model solves the nonhydrostatic form of the primitive equations on moving, nested grids; and uses a two-dimensional domain decomposition for efficient solution on scalable computer architectures. The ocean component of COAMPS also uses a 3-dimensional MVOI analysis that can assimilate in-situ and remotely-sensed observations, as well as incorporate subsurface thermohaline structure through the use of the Modular Ocean Data Assimilation System (MODAS) synthetic database. The hydrostatic NRL Coastal Ocean Model (NCOM) is the COAMPS ocean model.

In our study reported here, we generate multi-year atmospheric fields (analyses and forecasts) for the areas around and including the Mediterranean Sea and the Adriatic Sea, using horizontal grid spacings of 27 km and 4 km, respectively. These fields, generated at hourly intervals, include those necessary for forcing an ocean model (e.g., surface stress, sensible and latent heat fluxes, etc.). We use these fields to force NCOM to study how mesoscale weather events such as the Mistral (a strong northwesterly wind in the western Mediterranean) affect the mixed layer in the Mediterranean Sea. We have also found that the use of a 4 km grid is necessary to properly simulate the Bora, a strong northeasterly wind in the northern Adriatic. We use these fields to force NCOM, and measurements of Po River outflow in NCOM, to predict complex structures of the Adriatic circulation and thermohaline structure.

[1] COAMPS™ is a registered trademark of the Naval Research Laboratory.

Introduction

The U. S. Navy has a need for the analysis and prediction of the atmosphere and the ocean. Routine military exercises can be profoundly affected by variations in the atmospheric temperature, relative humidity, and wind; and by variations in the ocean currents, temperature, and salinity. These variations can significantly affect tactical parameters, such as radar propagation, acoustics, and visibility, which can be critical to the success of military missions. These variations typically occur over relatively small spatial and time scales, making them difficult to observe and to predict. In this paper, we address some of the issues of coupling atmosphere and ocean models, and study the ocean response to atmospheric forcing for significant weather events over the entire Mediterranean Sea, and in another set of experiments, the Adriatic Sea.

The atmosphere acts as the upper boundary condition for the ocean, and the surface atmospheric winds, temperature, precipitation, and radiation flux all play a strong role in forming and modulating the ocean circulation and thermohaline structure. There is mounting evidence that interaction with the ocean modifies the overlying atmosphere in important ways, as well. For example, recently Samelson et al. (2001) found that during coastal upwelling, the surface atmospheric temperature was cooled by 1-5 degrees on a 12-24 hour timescale by contact with the cooler ocean waters upwelled from depth. Also, Chelton et al. (2001) reported evidence of significant alterations in the observed equatorial surface wind stress field due to coupling between the atmospheric boundary layer and the underlying sea surface temperature. To fully account for these observed interactions as well as to anticipate the discovery of a host of other ways in which the ocean and atmosphere modify each other, NRL has undertaken the building of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS™; Hodur 1997). The goal of this modeling project is to gain predictive skill in simulating the ocean and atmosphere at high resolution on time-scales of hours to a several days. Significant questions exist as to how tightly coupled the atmosphere and ocean data assimilation systems must be, and over what types of atmospheric and ocean conditions this coupling is important. In this paper, we describe the modeling system that we use, COAMPS, and document tests performed with COAMPS on the effect of strong atmospheric forcing in the Gulf of Lion and in the Adriatic Sea. In the Gulf of Lion, we study the response of high-resolution atmospheric forcing on deep-water convection and formation. In the Adriatic, we study the response of the northern Adriatic Sea to the effects of the Bora wind and Po River runoff.

COAMPS Description

Atmospheric Component

There are four principal components of the COAMPS atmospheric data assimilation system. The first is the quality control of observations, in which observational data from many sources (e.g., radiosondes, aircraft, satellite, ships) are screened for errors, redundancy, and consistency with the previous forecast, etc. (Baker 1992). The second component is the analysis, in which the irregularly-spaced, quality controlled data are interpolated to the model's regularly-spaced grid. The interpolation method used by COAMPS is based on the multivariate optimum interpolation method (MVOI; Lorenc 1986). In the third component, model initialization, the analyzed fields are adjusted to conform to one of more dynamic and/or physical constraints. Finally, the fourth component is the numerical model, which integrates the initialized fields forward in time to a specified future time, using some approximate formulation of the primitive equations.

A great deal of flexibility has been built into COAMPS. First, the COAMPS grid can be set to any domain size and grid spacing at runtime, within the constraints of the computer system being used. Second, the grid can be located anywhere over the world, using one of 5 different map projections: polar stereographic, Mercator, Lambert conformal, spherical, or cartesian. Third, the system can be initialized with real- or idealized-data. Fourth, the model uses nested grids. The grid spacing is reduced by a factor of 3 between each nest. In this manner, the COAMPS grid can telescope down to resolutions of less than 10 km for areas in which high resolution is a necessity. Any number of nests can be defined at runtime. Fifth, a variety of lateral boundary conditions are available, supporting both real- and idealized-data experiments. Sixth, a single configuration managed version of COAMPS is used for all applications.

The atmospheric forecast model in COAMPS uses the nonhydrostatic form of the primitive equations as described in Klemp and Wilhelmson (1978). The nonhydrostatic form of the equations is necessary for modeling systems using a horizontal resolution less than approximately 10 km. For these resolutions, the vertical acceleration may become important, such as in convective systems or strong flow around steep topography. The COAMPS equations are solved on a staggered C-grid. COAMPS contains an advanced moist physics parameterization (Rutledge and Hobbs 1983), which is used in lieu of convective parameterization below 10 km grid spacing. This moist physics parameterization contains explicit equations for water vapor, cloud droplets, raindrops, ice crystals, and snowflakes. In addition, the COAMPS atmospheric model uses state of the art parameterizations for boundary layer processes and radiation.

The atmospheric portion of COAMPS has been operational at FNMOC since June 1998, and is currently run operationally over eight separate areas. Some of the areas utilize triply-nested grids with resolutions of 81, 27, and 9 km, while the remainder of the areas utilize a doubly-nested grid configuration using resolutions of 81 and 27 km. All COAMPS areas currently use 30 vertical levels, with the model top at approximately 34 km. The length of the COAMPS forecast varies based on the area and the nest. The longest forecasts extend to 72 h for 81 and 27 km grids, while the shortest forecasts (the 9 km grids) extend only to 24 h.

Ocean Component

The ocean analysis component of COAMPS is a fully 3-dimensional oceanographic implementation of the multivariate optimum interpolation algorithm that is used in the COAMPS atmospheric analysis component. The COAMPS ocean analysis component is executed in a sequential incremental update cycle, and a short-term model forecast (or previous analysis) provides the analysis background field. The theoretical basis of the multivariate method is described in Lorenc (1981) and Daley (1991). The ocean analysis variables are temperature, salinity, geopotential, and the u- and v-velocity components. Geopotential observations are calculated from observations of temperature and salinity assuming a level of no motion. The multivariate correlations compute geostrophically balanced increments of velocity from the analyzed increments of geopotential. In this way, adjustments to the ocean's mass field are correlated with adjustments to the ocean's flow field. The geostrophic coupling is relaxed near the equator and in shallow water where friction terms dominate the flow. To supplement the sparse subsurface observational data, the COAMPS ocean analysis system generates temperature and salinity profiles from the Modular Ocean Data Assimilation System (MODAS) synthetic database. The MODAS database contains coefficients that can be used to infer subsurface temperature structure from satellite altimeter sea surface height (SSH) observations and analyzed SST. Salinity is computed from temperature using climatologically based temperature-salinity relationships. The synthetic profiles are appended to the real-time observations and assimilated in the same way as any other observation, but with unique error characteristics specified.

The COAMPS ocean analysis system supports the same variety of map projections as used by the atmospheric components of COAMPS, and can be run on a nested grid structure at various grid resolutions producing multi-scale analyses. The update cycle of the COAMPS ocean analysis can be set independently of the atmospheric analysis update cycle, and post-time analyses can be run to process delayed-mode observations. Timely receipt of ocean observations is an important issue for a real-time system, and particularly so when the ocean forecast model is run in coupled mode with the atmospheric forecast model. The COAMPS ocean analysis system has been designed to handle the inevitable delays in the receiving and processing of observations at the production center.

The COAMPS ocean model is the Navy Coastal Ocean Model (NCOM) developed by Martin (2000). NCOM is designed to offer the user a range of numerical choices in terms of parameterizations, numerical differencing, and vertical grid structure. NCOM is based on the hydrostatic primitive equations, and has prognostic variables for the ocean currents, temperature, salinity, and surface height. An implicit formulation is used for the barotropic component. The equations are solved on the staggered C grid. One special aspect of NCOM is that it uses a hybrid vertical coordinate system. In this system, one can use all sigma-levels, all z-levels, or a combination of the sigma-levels for the upper ocean and z-levels below. Advection can be treated with second-order centered, or third-order upwind finite differencing. Options for boundary layer mixing include Mellor-Yamada 2.0 and Mellor-Yamada 2.5 schemes. The model also includes options for treating open boundaries using radiation conditions that have been successful in numerical models in the past.

A flux coupler has been developed to couple the COAMPS atmosphere and ocean models through the exchange of surface fluxes of heat, momentum, moisture, and radiation across the air-water interface, as well as to include the effects of precipitation falling into the ocean. Since the atmospheric and ocean models are expected to have different resolutions for many applications (and perhaps different grid projections, as well), the flux coupler has been designed to interpolate fields between the atmospheric and ocean grids to account for this differences. Special care is taken to ensure consistency of the forcing fields at the land/sea boundary.

Response of Deep-Water Convection and Formation to High-Resolution Atmospheric Forcing in the Northern Mediterranean Sea

Introduction

The Gulf of Lion, in the northwestern Mediterranean Sea, is a region where deep-water convection and formation are likely to occur during the winter season. The convection is strongly related to intense northwesterly winds in this area (i.e., the Mistral), which bring cold and dry air over pre-existing, weakly stratified water. In this study, the atmospheric component of the COAMPS is used to construct high-resolution reanalyses of surface fluxes over the Mediterranean Sea using all available observations. The period of this reanalysis is from October 1998 to September 2000. The fields generated from this reanalysis are used to force NCOM. The formation of deep-water convection due to high-resolution atmospheric forcing in the Gulf of Lion is investigated for the winters of 1998/1999 and 1999/2000.

Simulations Designed

Initially, NCOM was run for 20 years using monthly mean climatology wind stresses and heat fluxes (May, 1982) for the forcing. Following this, the COAMPS hourly high-resolution reanalyses from October 1998 to September 2000 were applied as surface boundary conditions for NCOM to continue the run after the 20-year spin-up. All the NCOM runs used the same grid, with a domain size of 576×288 and a horizontal grid spacing of 6 km. The atmospheric reanalyses were generated using a domain size of 193×97 with a horizontal spacing of 27 km.

Results

Our atmospheric reanalyses reveal that several Mistral events occurred during the winter of 1998/1999, as indicated by peak wind stresses and large negative buoyancy fluxes in Figure 1a. The strongest winter storm passed through the northwestern Mediterranean Sea on 11 Feb. 1999. This intense Mistral, with a maximum wind stress over 1.5 $Nm^{-2,}$ induced a total buoyancy flux loss of over 5×10^{-4} $Nm^{-2}s^{-1}$ in the Gulf of Lion. It resulted in strong currents following the direction of wind stress with maximum speeds of over 70 cm s^{-1}. A cyclonic gyre was present at 41.8 ^{0}N and 6.2 ^{0}E with a surface depression of over 45 cm. Strong surface cooling and evaporation triggered deep convection. The time series of the potential temperature at the center of the convection in Figure 1b exhibits vertical penetrations of the cooling from the surface. The Mistral events consistently reflected deepening of the mixed-layer. A strong Mistral in the early December 1998 eroded the pre-existing surface stratification, and the cooling mixed down to 500 m. Three Mistral events followed this time period and the vertical mixing was interrupted with warm surface water recapping between these events. The strongest cooling event occurred on 11 February 1999, mixing the cold water to 1800 m. The vertically well-mixed column of water remained until early March through mixing by subsequent Mistral events. The Levantine Intermediate Water (LIW), characterized by a warm temperature anomaly, advected into the area in mid-March, replacing the cold water produced earlier by the Mistral.

The winter of 1999/2000 was characterized by fewer and weaker Mistral events than during the winter of 1998/1999 (Figure 2a). Warmer mixed-layer temperature in the pre-conditioning phase resulted a less favorable situation for deep convection (Figure 2b). Surface cooling and vertical mixing did not erode the surface layer stratification until the end of December. The largest ocean response occurred following the 23 January 2000 event, which was the strongest Mistral during this winter. The maximum wind stress during this event was approximately 1.2 Nm^{-2}, and total heat flux loss was 1000 Wm^{-2}. The maximum wind induced current had an overall speed similar to that found during the 1998/1999 winter season. The surface depression of 25-30 cm covered a large area. The temperature decreases and the salinity increases were smaller than in 1998/1999, resulting in shallower winter convection. The deepest mixing reached 1400 m following the strongest Mistral. The well-mixed column of water was re-stratified within a few days, and the LIW returned by early March.

Coupled air-ocean nested modeling studies of the Adriatic Sea

Introduction

The main aim in this component of our work, is to investigate the response pattern of the northern Adriatic Sea to the complex combined forcing of the Bora winds and strong Po River run-off. In addition to investigating complicated physical processes in the northern Adriatic Sea, we are carrying out model-data validation efforts in coordination with a suite of observations that will take place in the Adriatic Sea beginning in the fall season of 2002.

We have focused on the time period of winter and spring 2001 when there were several Bora wind events documented by the pilot program observations taken in preparation for the fall and winter 2002-2003 Adriatic Current Experiment (ACE). In addition, we analyze results from a multi-month simulation in fall/winter 1999 to establish circulation patterns that may appear during the upcoming observational season. The ACE fixed location observations will include bottom-mounted ADCP’s, moored buoys, and CTD sections. Additional measurements using surface radar, airborne salinity mapping, towed undulating vehicles, and drifter release are planned. The observational programs will generate much data about the circulation of this shallow sea subjected to river floods and strong Bora wind events.

The main goals of our work are to validate the modeled fields against observations, and to statistically catalog and analyze the canonical ocean and atmosphere dynamical responses to intense, episodic forcing. To achieve these goals requires very high resolution grids for both the atmosphere and ocean models. The system we have configured is designed to resolve processes operative on small scales in both the ocean and atmosphere.

Model Configuration

We conduct simulations of the Adriatic Sea using NCOM, with surface forcing provided by the atmospheric component of COAMPS. Separate three-dimensional multivariate optimum interpolation (MVOI) analysis techniques are used to generate the initial conditions for both COAMPS and NCOM. First, we used a 6-km NCOM grid over the entire Mediterranean Sea, with forcing supplied by surface fluxes (momentum and heat) from a 27-km COAMPS grid, also covering the entire Mediterranean Sea area. Both the atmospheric and ocean fields produced were part of independent 12-hour incremental data assimilation cycles over the time period of interest. The resulting NCOM forecasts were then used as lateral boundary conditions for a series of higher resolution (2 km) NCOM forecasts of the Adriatic Sea. In these forecasts, a set of surface flux fields from COAMPS, using a nested 4 km grid centered over the Adriatic Sea, were used to force the NCOM high-resolution ocean nest (Figure 3). In addition, the 2 km Adriatic Sea model is forced by observed daily river discharge values from the Po River.

Results

The northern Adriatic atmospheric circulation is characterized by two distinct wind patterns termed “Bora” and “Scirocco.” The Bora is a strong wind flow from the northeast that is a maximum in the lee of the Dnirac Alps. Wind speed maxima extend eastward over the northern Adriatic and are present on either side of the Istra peninsula, with a distinct wake apparent in the lee of the peninsula (Figure 4). Winds coming from the northeast exceed 5 m/s over 25% of the time (maximum of 41.2%) in this region. These winds extract a great deal of heat from the ocean and create local areas of dense water formation. The Scirocco pattern consists of strong winds from the southeast that are intensified along the eastern side of the Adriatic Sea. Winds coming from the southeast exceed 5 m/s along the eastern Adriatic over 25% of the time (maximum of 41.9%). The localization of this pattern along the Croatian mountain ranges suggest the manifestation of a blocking phenomenon.

These patterns of wind forcing create complex structures in the ocean circulation (Figure 5). For instance, during the occurrence of a Bora event on 5 October 1999, the Po River plume expands offshore with the low-salinity plume water spreading out in the upper 10 m of the water column. Two days later the plume is subjected to locally downwelling favorable winds as the atmospheric circulation shifts, and the plume is consequently pushed against the coast, while deepening and mixing through the water column. Finally, on 9 October 1999, under the influence of locally offshore-oriented winds, the plume moves offshore and stratified conditions begin to be re-established. Thus the dynamics of the river plume are highly variable and extremely sensitive to the details of the atmospheric forcing.

Future model validation efforts will focus on verifying the magnitude, temperature, and vertical structure of Adriatic coastal currents from upcoming observations and on quantifying the dynamical response of the ocean to the atmospheric forcing regimes documented above.

Conclusions

The Naval Research Laboratory is developing and testing an ocean data assimilation component of COAMPS. The ocean component includes data quality control, 3-dimensional analysis capability through the multivariate optimum interpolation technique, and prediction capability through a hydrostatic, free-surface ocean model. The COAMPS ocean model is coupled to the COAMPS atmospheric model through a generalized flux coupler. The flux coupler allows for different grid projections and different grid resolutions between the atmospheric and ocean grids.

It is critical that analyses and predictions of the ocean be forced with high-resolution atmospheric fields in order to develop the proper structures in the ocean. In this project, we are generating high-resolution fields with the atmospheric data assimilation of COAMPS using resolutions as high as 4 km. These fields serve as a baseline for the validation of the atmospheric component of COAMPS. It is important to establish this capability in order to measure the impact of adding ocean coupling to the atmospheric forecasts. The reanalysis fields also are used for input to the COAMPS ocean model in our one-way coupled tests, and demonstrate the importance of high-resolution modeling in coastal areas and areas dominated by significant topographic features.

Our reanalyses validate the skill of COAMPS, demonstrate the need to use proper data assimilation methods to retain information from observations taken at previous times, and demonstrate the need to use unfiltered model output on the native model grid for forcing ocean models.

Within our air-ocean coupling work, we are testing the abilities of the ocean component of COAMPS in two ways. First, we are performing experiments to study the effect of the Mistral, a strong, cold northwesterly wind that occurs in the Gulf of Lion, on the formation of deep-water convection. Second, we are studying the impact of the Bora, a strong northeasterly wind that occurs over the northern Adriatic Sea, and outflow from the Po River, on the circulation and thermohaline circulation in the Adriatic Sea.

Acknowledgments

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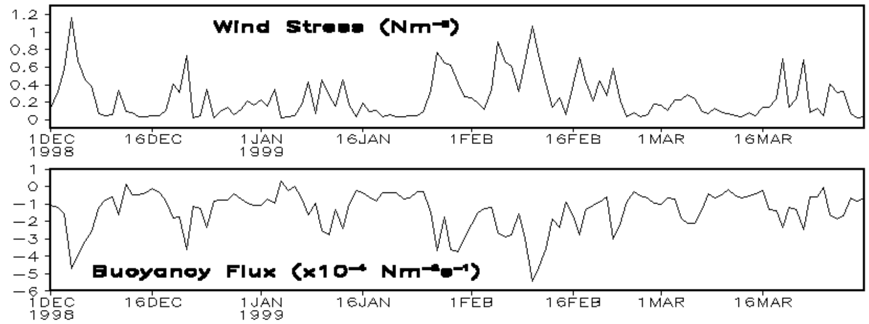

Figure 1a. Area-averaged atmospheric surface wind stress (upper panel) and buoyancy flux (lower panel). The area is in the box of 41-43 ^{0}N and 3.5-7 ^{0}E.

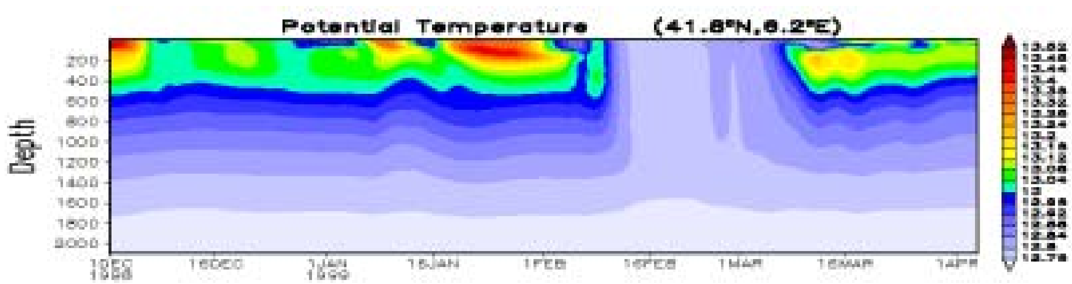

Figure 1b. Time series of potential temperature at point 41.8 ^{0}N and 6.2 ^{0}E for the winter 1998/1999.

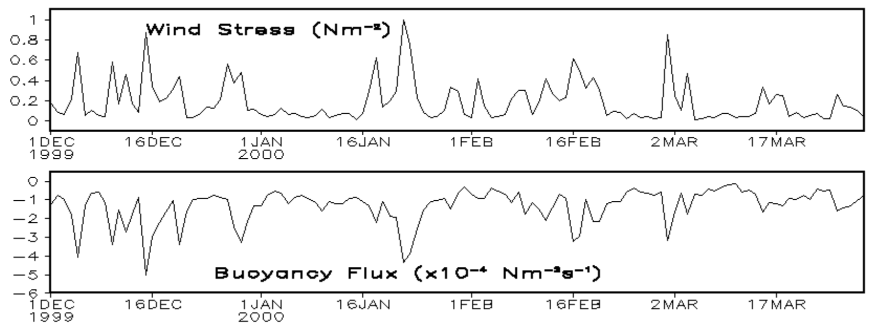

Figure 2a. Area-averaged atmospheric surface wind stress (upper panel) and buoyancy flux (lower panel). The area is in the box of 41-43 ^{0}N and 3.5-7 ^{0}E.

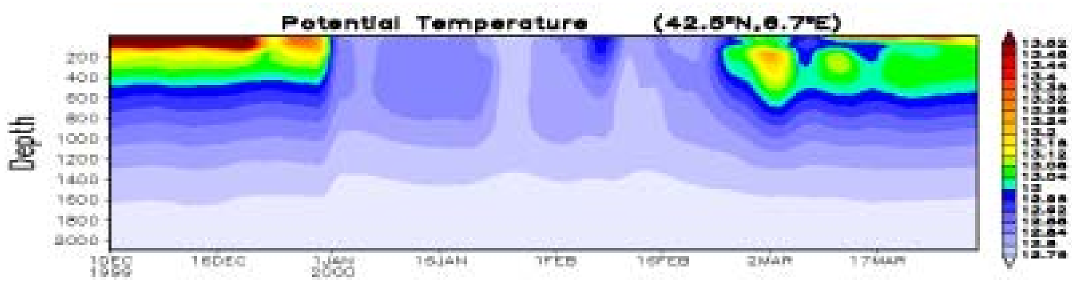

Figure 2b. Time series of potential temperature at point 42.5 ^{0}N and 6.7 ^{0}E for the winter 1999/2000.

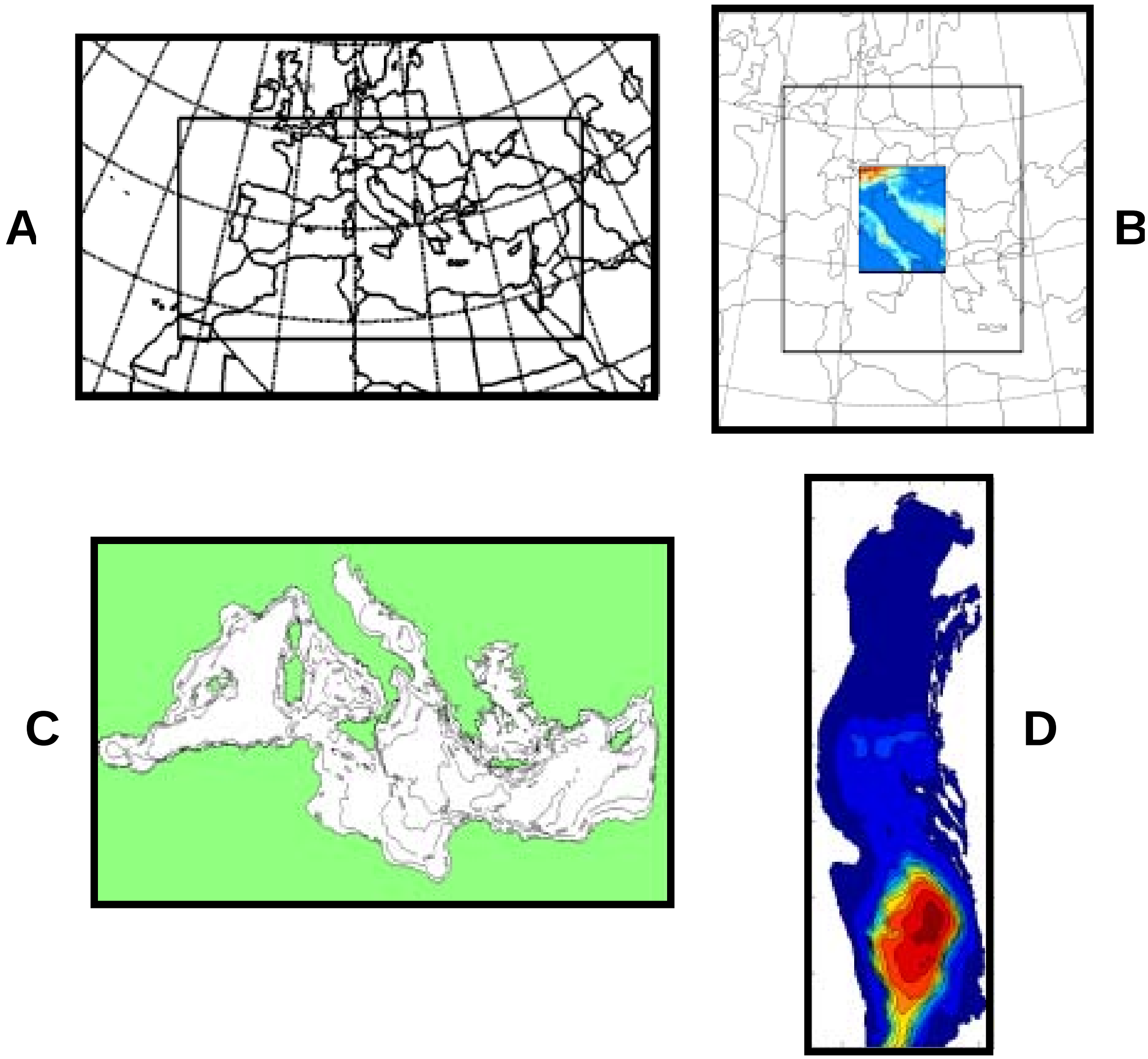

Figure 3: Nested grid configuration for the COAMPS atmospheric model (a) using 81/27 km nests for the Mediterranean Sea, and (b) using 36/12/4 km nests for the Adriatic Sea. Grid configurations for NCOM (c) using 6 km resolution for the Mediterranean Sea and (d) 2 km resolution for the Adriatic Sea. The color contours on the atmosphere and ocean Adriatic grids represent terrain height and bathymetry, respectively.

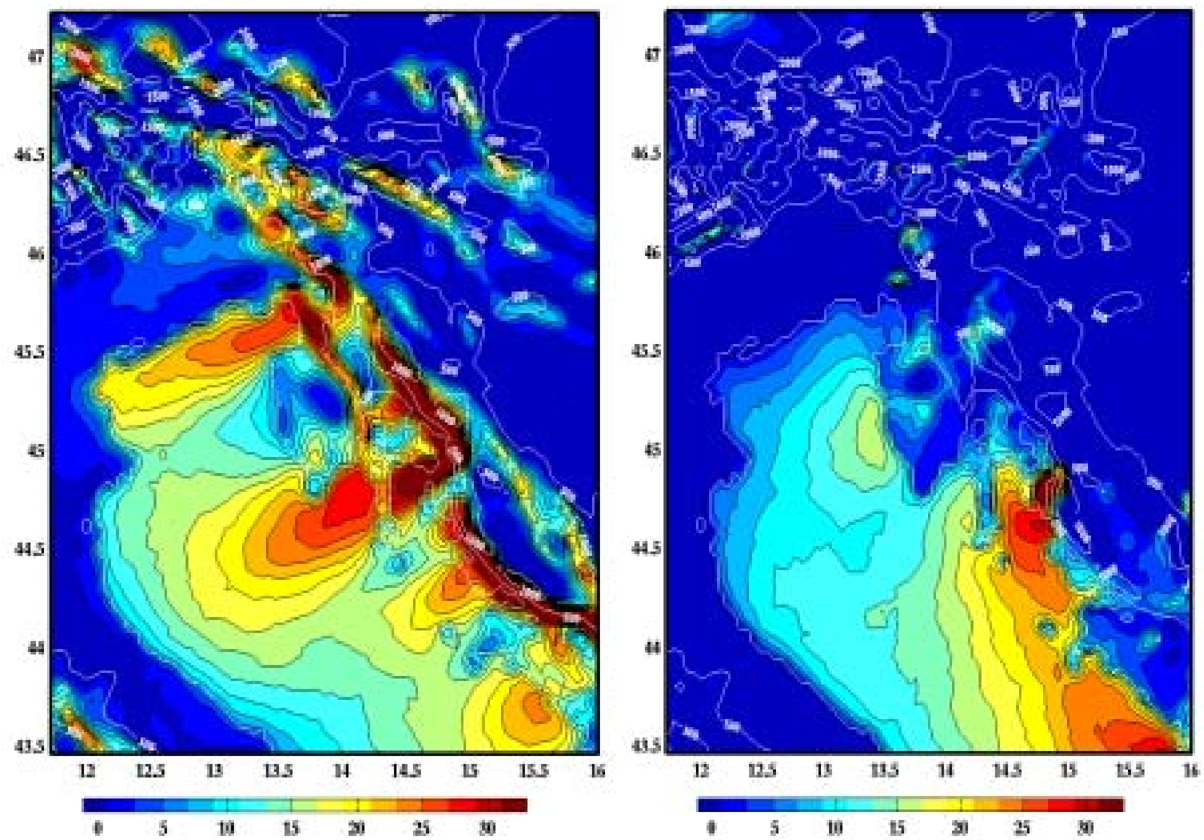

Figure 4. Frequency maps based on hourly COAMPS 10 m winds from 15 January – 1 June 2001 for the 4 km nested grid. The left panel represents the percentage of time that the wind speed exceeds 5 m/s and comes from the northeast quadrant (Bora orientation). The right panel represents the percentage of time that the wind speed exceeds 5 m/s and comes from the southeast quadrant (Scirocco orientation). Terrain heights are indicated in white lines and contoured in meters.

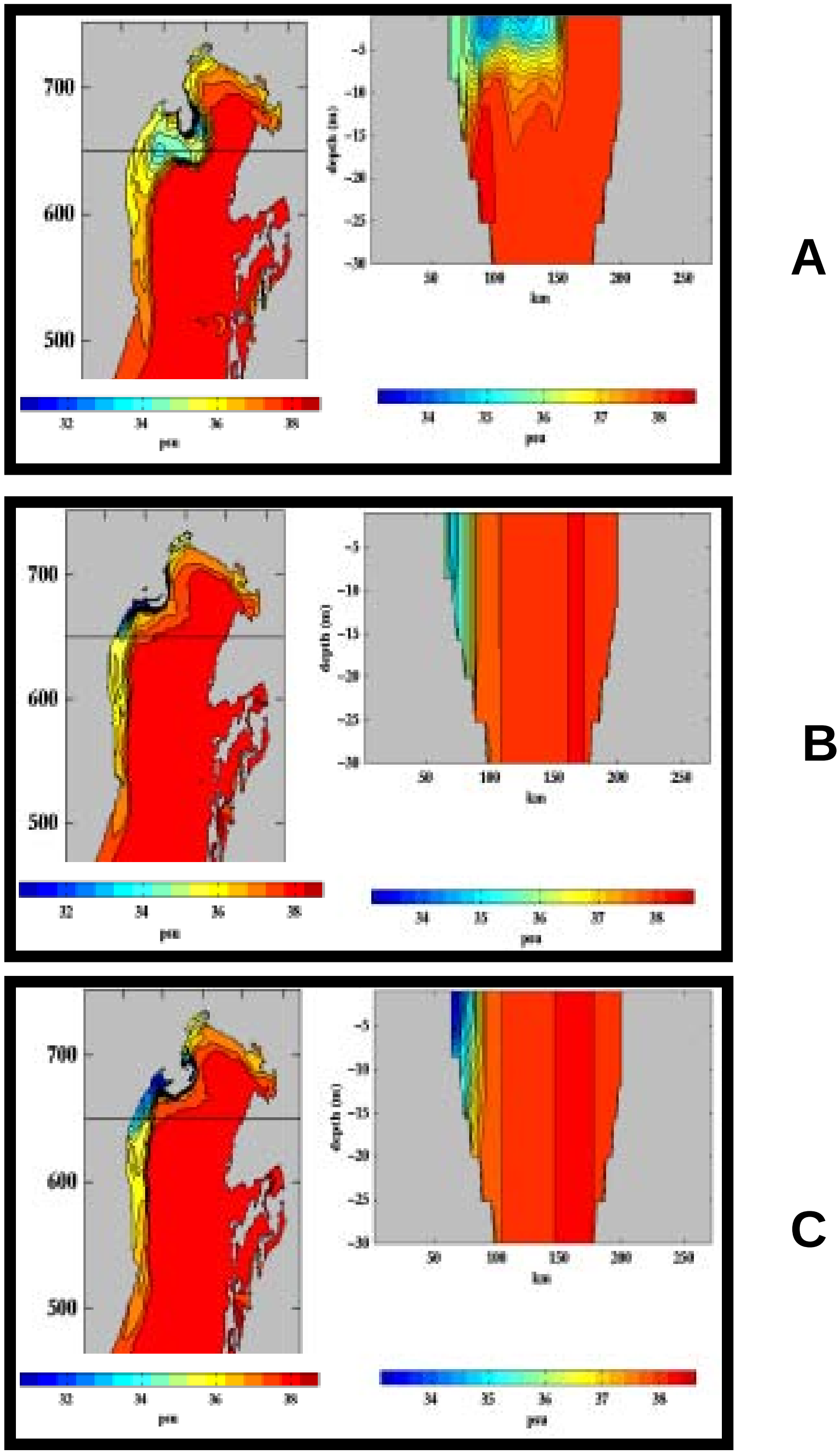

Figure 5: Evolution of ocean model salinity on (a) 5 October 1999, (b) 7 October 1999, and (c) 9 October 1999 in the northern Adriatic in response to the relaxation of winds from a Bora state. The location of the depth transect is indicated on the map and cuts through the Po River plume. These model results come from the 2 km resolution NCOM ocean model covering the Adriatic Sea.